

Investigation of HAPs Propagation Channel for Wireless Access in a Tropical Region at Ka-band

Felix Obite¹, Jafri Din², Kamaludin Mohammad Yusof³, Basliza M. Noor⁴

^{1,2,4}Wireless Communication Center, Faculty of Electrical Engineering, 81310 UTM Johor Bahru, Johor, Malaysia

¹Department of Physics, Faculty of Science, Ahmadu Bello University, P.M.B. 1044, Zaria, Nigeria

³Department of Communication Engineering, Faculty of Electrical Engineering, 81310 UTM, Johor, Malaysia

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ABSTRACT

In the last few years, High Altitude Platforms (HAPs) have attracted considerable effort due to their ability to exploit the advantages of satellite and terrestrial-based systems. Rain attenuation is the most dominant atmospheric impairment, especially at such frequency band. This paper addresses the modelling of rain attenuation and describes a propagation channel model for HAPs at Ka-band to provide efficient and robust wireless access for tropical regions. The attenuation due to rain is modeled based on three years measured data for Johor Bahru to estimate the actual effect of rain on signals at Ka band. The radio propagation channel is usually characterized as a random multipath channel. Specifically, a statistical derivation of probability distribution function for Rayleigh and Rician fading channels are presented. The model consists of multiple path scattering effects, time dispersion, and Doppler shifts acting on the HAPs communication link. Simulation results represent the fading signal level variations. Results show perfect agreement between simulation and theoretical, thereby conforming to the multipath structures. The information obtained will be useful to system engineers for HAPs link budget analysis in order to obtain the required fade margin for optimal system performance in tropical regions.

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Corresponding Author:

Jafri Din,
Wireless Communication Center,
Faculty of Electrical Engineering,
81310 UTM Johor Bahru, Johor, Malaysia.
(Fax) +(6)07-5535252, Tel +(60)07-5535306
Email: jafri@utm.my

1. INTRODUCTION

The rising demand for wireless broadband communications has informed the implementation of HAPs systems as a novel technology to the existing satellite or terrestrial wireless communication networks. HAPs are aircraft or airships functioning at stratospheric altitudes of 17 to 25 km [1]. At this height, since the wind speed is insignificant, they can be used to deliver cellular services and broadband communications especially in remote areas lacking network infrastructures. Also, at these heights, the signal propagation delay is less compared to the satellite signal. Though HAPs are an old concept, it is only lately, that they have been conceived as a key technology in the next generation of heterogeneous networks. The International Telecommunication Union (ITU) have permitted HAPs to operate at 31/28 gigahertz for Asian regions [1], [2] and 47/48 gigahertz for other countries [1], [3]. Even though these frequencies are characterized by harmful propagation impairments, they are envisaged for mobile broadband and fixed wireless access. In order to maintain a quasi-error free system, the line-of-sight (LOS) channel situations are necessary for fixed wireless broadband communication systems functioning at the millimeter-wave

frequencies. In mobile propagation channel, the LOS is blocked occasionally by several obstacles, such as mountains, buildings or shadowed by vegetation. Consequently, the radio signal experiences a complete blocking or deep fading [4]. However, atmospheric effects such as rain attenuation, even in the LOS channel condition, may cause serious signal degradation at higher frequencies. In the Ka frequency band, liquid rain droplets in the form of scattering and absorption contribute to propagation losses [5]. The attenuation is a function of frequency, latitude, specific attenuation, temperature, polarization and path length.

There are several existing statistical channel models for land mobile satellite (LMS) communication systems. Nevertheless, they are not directly applicable to HAPs communication systems due to significant differences between stratospheric and satellite propagation conditions. Thus, we adopt the existing LMS channel model and modify it for HAPs communication system bearing in mind the specifics of the stratospheric propagation channel, such as different carrier frequency and variable elevation angle. While several active studies have been carried out relating to HAPs aeronautical features such as [6], [7]. In [8], [9] a statistical model of smaller scale fading for HAPs channel propagation was presented. The model considered 2 GHz frequency range and rain attenuation effects were not considered since they are negligible at such frequency range. The authors in [4] have discussed modeling of atmospheric impairments for stratospheric communications at Ka band, the attenuation due to rain was modeled using the modified DLR approach [10], [11]. This paper addresses the modelling of rain attenuation and describes a propagation channel model for HAPs at Ka-band to provide efficient and robust wireless access for tropical regions. We model the HAPs propagation channel as a Rayleigh and Rician fading channel that can simulate a real-world scenario in mobile communication. In particular, a statistical derivation of probability distribution function for Rayleigh and Rician fading channels are presented. The model includes multiple path scattering effects, time dispersion and Doppler shifts acting on the HAPs communication link.

This paper is organized as follows. Section (2) discusses rain attenuation at Ka frequency band, where the rainfall rate and rain attenuation CCDF for Johor Bahru is presented based on measured data. Section (3) is devoted to the channel modelling where we perform the statistical modelling and analysis of the HAPs propagation channel. Simulation results and discussion are presented in Section (4). Finally, we conclude the paper in Section (5)

2. RAIN ATTENUATION AT KA-BAND

Rain attenuation has been identified as the major source of atmospheric attenuation in land mobile satellite communications above 10 GHz [12]. Rain fading constitutes signal attenuation as a result of precipitations, clouds, and other atmospheric phenomena [13] where rain is the most dominant fading impairment. This will cause sporadic signal attenuation in the HAPs mobile communication link operating at Ka frequency bands. The effect of rain fading on the radio signal largely depends on the rain rate, such as (drizzle, showers, and heavy rain). Considerable efforts have been recorded in the last few years to characterize the statistical and random nature of rain rate and rain attenuation [14]. It is desirable to have adequate information of the rain attenuation in order to plan a reliable communication system at such frequency range. This has become very crucial for tropical regions due to their high rainfall intensity. In order to extract the rain characteristics of any particular region, it is required to consider a percentage of less than 1% of the time of the year. This is usually the case since it contains the amount of rainfall that causes a severe loss of the transmitted signal. Also, in tropical regions, a heavy rain rate usually occurs at 0.01% of the time causing a significant issue to the received signal quality. Thus, when analyzing the effect of rain attenuation, 0.01% of the annual time is the most appropriate percentage, especially at Ka band.

A number of researchers [15-17] have developed rain attenuation prediction models which have attracted global recognitions, including the ITU-R rain attenuation prediction model which is based on 0.01% rain rate per year [18], [19]. These models were developed for temperate regions and yet, estimated to be applied to tropical regions. Several studies [20-23] have shown that the models recorded a high inaccuracy level when applied to tropical regions based on specific atmospheric parameters. The authors have proved that the ITU-R model is only applicable for predicting rain attenuation at lower operating frequency in tropical Malaysia. Particularly, when the measured data was compared with the ITU-R model at Ka-band, and at higher rain rate, the ITU-R model was not suitable for predicting rain attenuation at higher frequencies.

We adopted a model proposed by the authors in [24] based on measurement results. A path length of 5.83km link was set up in Johor Bahru, Malaysia. The transmitter and receiver were operating at 15 GHz frequency. At every minute interval, the levels of the signal received were sampled. A rain gauge (Casella) was mounted at the measurement location to collect 3 years precipitation data from January 2006 to December 2008. These sampled data is utilized to examine the radio link. The rain attenuation data and precipitation data was simultaneously recorded. The rain gauge employed is a tipping bucket kind with 0.5

mm sensitivity. The rain gauge records the whole rainfall happening in every minute without capturing non-rainy events; thus the captured rain rate is an integral multiple of 0.5 mm/min or 30mm/h. The link specifications are shown in Table 1, while Figure 1 illustrates the rainfall rate complementary cumulative distribution function (CCDF) for an average of three years in Johor, Malaysia. The graphical plot is intended to illustrate the rain rate relationship at different time percentage during the experimentally collected data period. The rain rate observed at 0.01% of the time was recorded to be 125 mm/hr [24]. Additional analysis was also conducted to assess the effects of rain attenuation on the link at 26 GHz frequency. To obtain the rain attenuation values at this higher frequency, the frequency scaling technique is used by inverting the existing 15 GHz rain attenuation data [25].

$$A_2 = A_1 (\Phi_2 / \Phi_1)^{1-H(\Phi_1, \Phi_2, A_1)} \quad (1)$$

where:

$$\Phi(f) = \frac{f^2}{1 + 10^{-4} f^2} \quad (2)$$

$$H(\Phi_1, \Phi_2, A_1) = 1.12 \times 10^{-3} (\Phi_2 / \Phi_1)^{0.5} (\Phi_1 A_1)^{0.55} \quad (3)$$

Where A_1 and A_2 are the probable equivalent excess rain attenuation values at f_1 and f_2 frequencies in GHz respectively.

Table 1: The 15 GHz link specifications [24]

Link location	Hop length (km)	Frequency band (GHz)	Maximum transmit Power in (dBm)	10^{-6} BER (2×2 Mbps) received threshold	Antenna for transmitting and receiving side Size (m)	Gain (dBi)
Johor Bahru	5.83	15	+18.0	-84.0	0.6	37.0

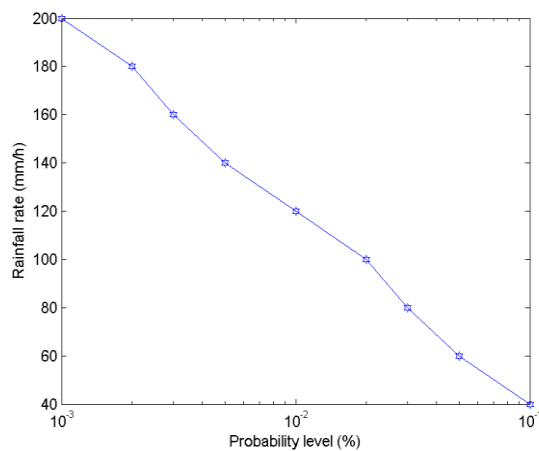


Figure 1. Rain rate CCDF for Johor Bahru

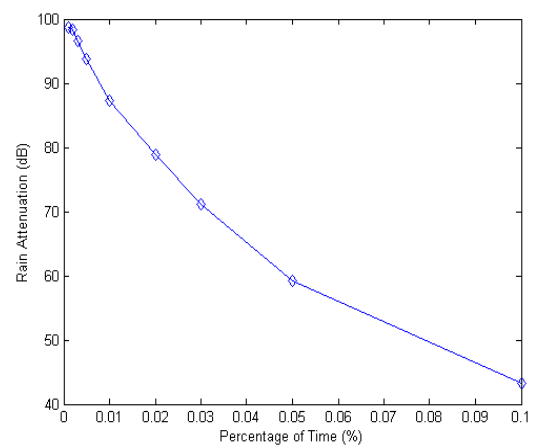


Figure 2. Rain attenuation CCDF at Ka-band for Johor Bahru

Thus, Figure 2 shows the complementary cumulative distribution function (CCDF) of rain attenuation characteristics using three years measured data for Johor Bahru as shown in Table 2. Similarly, as shown in Figure 2, at 0.1% and 0.01%, the measured rain attenuation at Ka-band frequency is 43.18 dB and 87.23 dB respectively.

Table 2. Measured rain attenuation at 26GHz [24]

Percentage of Time (%)	Rain Attenuation (dB)
$f = 26\text{GHz}$	
0.1	43.18
0.05	59.26
0.03	71.14
0.02	78.83
0.01	87.22
0.005	93.84
0.003	96.65
0.002	98.40
0.001	98.60

3. CHANNEL MODELLING

In this section, we perform the statistical modelling and analysis of the HAPs propagation channel at 28/31 GHz. The stratospheric communication system behaves similarly to the land mobile satellite communication system. The visibility of the platform is often blocked by several obstacles such as mountains, buildings, hills and vegetation resulting in two propagation extreme phenomena known as the LOS and NLOS conditions as shown in Figure 3. As an application example of the model, we consider a signal carrier frequency $f_c = 28\text{GHz}$. The platform is situated at 22 km altitude from the surface of the earth having a speed $v_p = 150\text{km/h}$ and a mobile terrestrial user speed $v_u = 50\text{km/h}$ with elevation angle $\psi_u = 60^\circ$. The elevation angle was chosen in order to meet the minimum operational elevation angle as specified by ITU-R [26].

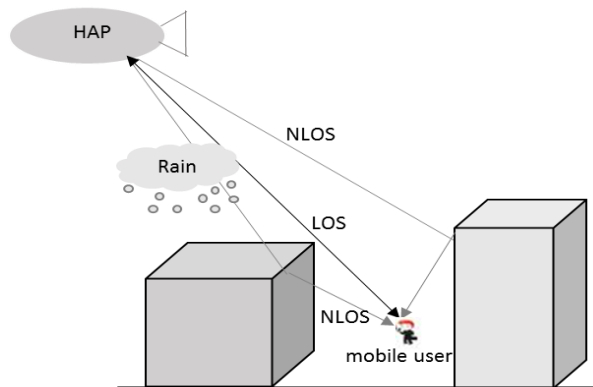


Figure 3. HAPs system scenario

3.1. Rayleigh Fading Channel

Rayleigh fading can be used to model NLOS path existing between transmitter and receiver [27]. For urban environments (deeply built-up areas) the signal transmitted will arrive on the receiver via multiple path propagation components. The resultant received signal is a summary of diffused multiple path mechanisms described by several delays, impairments, and phase changes. As the amount of paths increases, the sum tends to a complex random Gaussian variable with real and imaginary components having zero mean with identical variance. The signal amplitude follows a Rayleigh fading while the periods of specific components are distributed uniformly in 0 to 2π interval. The received signal is given by

$$s(t) = \sum_{i=1}^n a_i \cos(\omega_c t + \phi_i) \quad (4)$$

Where n is the number of indirect components, $a_i(t)$ the signal amplitude, ϕ_i the multiple path phase and ω_c denotes angular frequency. Due to the relative motion between the terrestrial mobile user and the platform, the equation (4) must be modified so as to take consideration of Doppler shifts. Let the reflected i th ray reach the receiver relative to the antenna directions from angle ψ_i . The Doppler shift with angular frequency is given by

$$\omega_{di} = \frac{\omega_c (v_p + v_u)}{c} \cos \psi_i \quad (5)$$

v_p denote the HAPs speed, v_u is the speed of the mobile terrestrial user, c is the speed of light.

The received signal is modified and expressed as

$$s(t) = \sum_{i=1}^n a_i \cos(\omega_c t + \omega_{di} + \phi_i) \quad (6)$$

Note that the terrestrial-to-HAP link has little delay spread, hence an insignificant time-based dispersion, that is selective in wideband signals [28]. Also, the frequency dispersion as a result of Doppler spectrum is usually critical than land channels, due to the motion of both the HAP and the mobile terrestrial user.

In a Rayleigh fading channel, the probability density function (PDF) of the signal received is given by

$$f(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \text{ for } r \geq 0 \quad (7)$$

Where σ represents the standard deviation and r denotes the received signal envelope.

3.2. Rice Fading Channel

Rice fading arises when LOS components exist together with multiple path components between the transmitter and the receiver [28]. In the context of HAPS, the transmitted signal is given by

$$s(t) = \sum_{i=1}^n a_i \cos(\omega_c t + \omega_{di} + \phi_i) + k_d \cos(\omega_c + \omega_d t) \quad (8)$$

Where k_d denotes the strength of the LOS signal. Other factors remain constant as defined by Rayleigh fading channels. The received signal PDF for a Rician distribution is expressed as

$$f(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + k_d^2}{2\sigma^2}\right) I_0\left(\frac{rk_d}{\sigma^2}\right), \text{ for } r \geq 0 \quad (9)$$

Where I_0 represents the zero order modified Bessel function of the first kind and $k_d^2/2$ the LOS average power. When there is a shadow or blockage between the platform and the terrestrial user, (i.e $k_d = 0$) the

equation above becomes a Rayleigh distribution. $k_d^2/2\sigma^2$ is known as the Rician factor expressed in decibels.

4. RESULTS AND ANALYSIS

Based on the previous analysis, a MATLAB-based simulation approach for HAPs propagation channel is presented. The fading process, typically, is characterized by Rayleigh distribution for NLOS path and a Rician distribution for LOS path. MATLAB uses a `rand` function which creates distributed uniformly samples: `rand(1000,1)*360`.

Figure 4 shows the Rayleigh simulated received signal envelope, varying below 0dB (LOS level), which approximately is -20dB . It is evident that the signal fluctuation in the Rayleigh channel is more rapid and larger than the Rician channel, and this is attributed to NLOS existing between the platform and the mobile user. Thus, the size of the signal power determines the amount of signal loss which is more apparent in the Rayleigh channel than the Rician channel. The simulated signal and theoretical CDF show a good fit as shown in Figure 5.

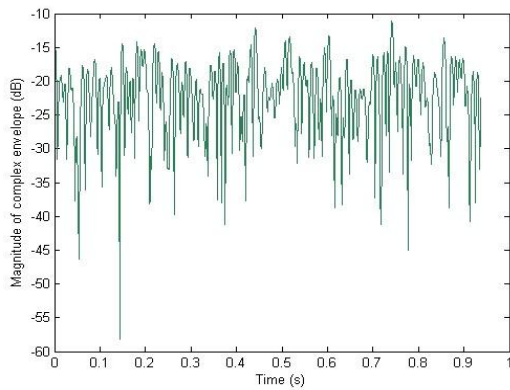


Figure 4. Rayleigh Simulated Received Signal Envelope

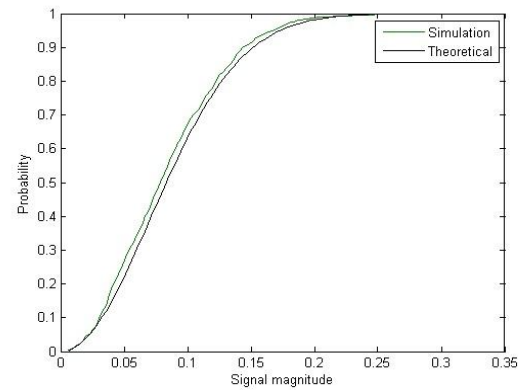


Figure 5. Rayleigh Simulated Signal and Theoretical CDF

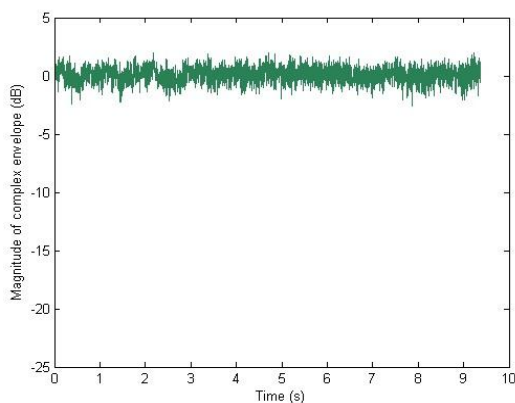


Figure 6. Rician Simulated Received Signal Variations

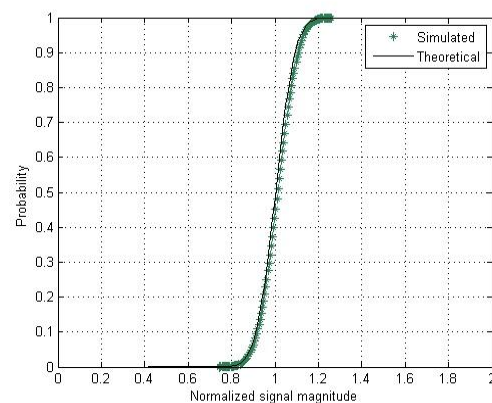


Figure 7. Rician Simulated Signal and Theoretical CDF

Figure 6 shows the Rician simulated received signal variations. As noticed, the received signal levels change drastically. The variations are around the 0dB level, but in the Rayleigh case, they were around

−20dB. The fluctuations dynamic range has changed, also the fades are less deep compared to the Rayleigh case. This is due to the presence of direct LOS, posing fewer obstacles to the signal transmitted. The simulated signal and theoretical CDF show a perfect match as shown in Figure 7.

5. CONCLUSION

In this study, rain attenuation and statistical modelling of HAPs propagation channel for wireless access in a tropical region are presented. The attenuation due to rain at higher operating frequency is the most dominant atmospheric impairment on the air-to-ground link. Thus, we model the rain attenuation based on three years measured data for Johor Bahru to estimate the actual effect of rain on Ka band signals. This information will be useful to researchers to make adequate deductions regarding rain rate and rain attenuation prediction for HAPs communication link operating at Ka-band in a tropical region. The channel model includes multipath scattering effects, time dispersion, and Doppler shifts acting between the platform and the mobile user. Simulation results represent the fading signal level variations. Results revealed a perfect agreement between simulation and theoretical, thus conforming to the proposed model.

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